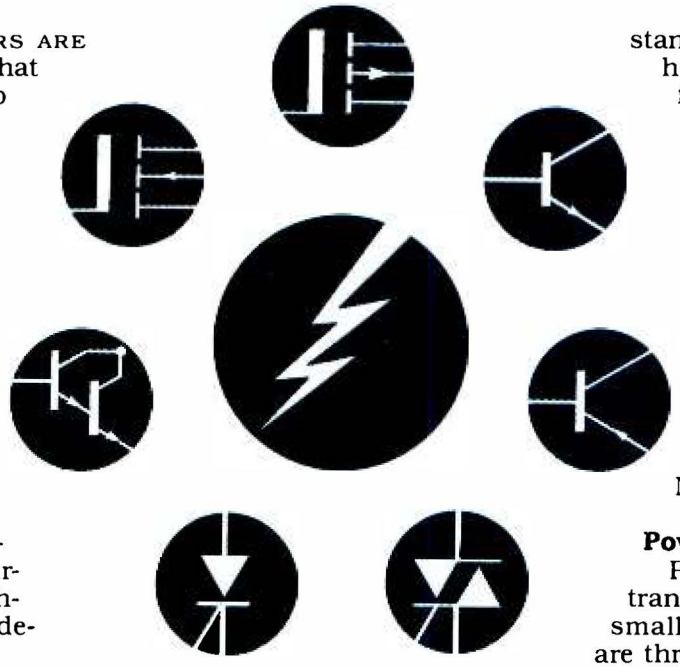
POWER SEMICONDUCTORS



NEIL SCLATER

Semiconductors from transistors and thyristors to solid-state relays and integrated circuits have been designed to switch high currents and voltages, making them power devices.

POWER SEMICONDUCTORS ARE semiconductor devices that have been designed to handle or switch power. They include bipolar and field-effect transistors, thyristors, solid-state relays and a fairly new class of device called the power ICs.

There is no industry-accepted definition that will apply to all power semiconductors. However, most should be capable of passing at least 1 ampere of current or handling 1 watt of power during normal operation without being damaged or destroyed.

Some semiconductor devices are rated for handling voltages and currents that are far beyond those normally encountered in electronics. They are more properly classed as electrical power and distribution components, but there is no agreement on the boundaries between those classifications. They are best determined by their applications.

Many people think of power semiconductors as components found only in automotive, industrial, and military circuits, but they are now found in many consumer appliances, entertainment products, and business machines. Not so long ago it was easy to distinguish a power semiconductor device from a small-signal device—they were in metal cases.

Today, a surprisingly large number of mid- and low-range power devices are packaged in plastic cases because of the development of improved, low-cost plastic cases that will withstand thermal stress. Some have metal tabs that function both as heatsinks and mounting surfaces.

Power transistors

Three types of discrete transistors qualify as power transistors: power bipolar junction transistors (BJT), power bipolar Darlington transistors, and power MOSFETs.

Power bipolar transistors

Power bipolar junction transistors (BJT), like their small-signal counterparts, are three-layer, three-terminal devices formed by adding a second junction to a two-layer diode chip. Figure 1 is the schematic symbol for an NPN BJT; it is the same symbol as that for a small-signal BJT. Power BJTs also have emitter, base, and collector terminals. In normal operation, the emitter-to-base junction is biased in the forward direction, while the collector-to-base junction is reverse-biased.

Electrons flow from the emitter to the collector in all BJTs (opposite the flow of conventional current). However, the outward-pointing arrowhead in Fig. 1 shows the direction of conventional current. Figure 2 is the schematic symbol for a power PNP BJT. Here electron flow and conventional current are reversed. This can be seen from the inward direction of the arrowhead. (For more information on all BJTs refer to the September 1993 *Electronics Now*, page 57.)

Both kinds of power BJTs are

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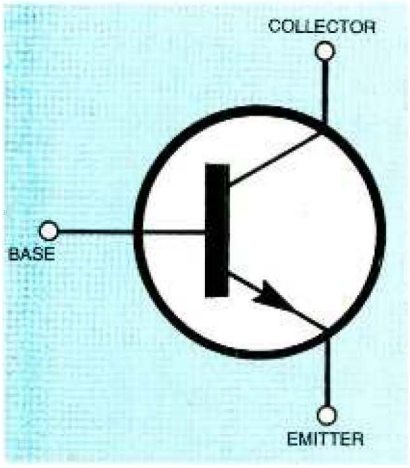

FIG. 1—SCHEMATIC SYMBOL for an NPN power bipolar junction transistor (BJT).

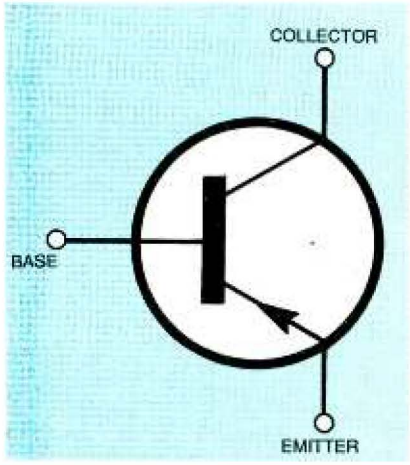

FIG. 2—SCHEMATIC SYMBOL for a PNP power bipolar junction transistor (BJT).

made as two parallel PN junctions with controlled spacing between their junctions and controlled impurity levels on both sides of each junction. This is shown in Fig. 3, the functional diagram for an NPN showing the polarities for conventional operation.

In power BJTs, *structure* refers to the junction depth, the concentration and profile of the impurities (doping), and the spacing of the various levels of the device. Figure 4 is a cross-section view of an NPN BJT formed as a vertical silicon structure. The collector terminal is at the base of the chip, but both the base and emitter terminals are on the top.

The term geometry refers to the topography of the transistor, that is, the way the various doped parts of the transistor are formed on the silicon chip or die.

The applications for power BJTs are influenced by their structure, geometry, and packaging. When selecting a power BJT, the circuit designer must consider gain, frequency, voltage, current, and the heat dissipation characteristics of the device.

BJT structures

Various power transistor structures have been developed to provide different electrical and thermal characteristics at different price levels. Each has advantages and disadvantages or compromises. BJT structures can be classified in terms of the number of diffused layers, the use of an epitaxial base, or combinations of these.

Some power BJTs have a *mesa* structure and others have a *planar* structure. In textbooks and manufacurers' data books you will see references to specific structures:

1. Single-diffused (hometaxial)
2. Double-diffused (mesa, planar, epitaxial mesa, planar mesa, and multiple epitaxial mesa)
3. Triple-diffused (mesa and planar)
4. Epitaxial-base (mesa)
5. Multiple-epitaxial base (mesa)

A discussion of these structures and how they are formed is beyond the scope of this article. However, each of these structures has its own set of characteristics that make them suitable for handling high voltages, current, and power. Some structures are best suited for power switching while others function better as large-signal amplifiers including radio frequency (RF) amplification.

There also economic considerations. Some structures cost more to manufacture than others and this is reflected in their pricing. If a metal case is required, or a wider operating temperature is needed, expect to pay more for the device.

Power BJTs are specified in terms of the following parameters:

1. Voltage rating, collector-to-emitter.
2. Current rating of the collector.
3. Power rating.
4. Switching speed.
5. Direct-current gain.
6. Gain-bandwidth product.
7. Rise and fall times.
8. Safe operating area (SOA).
9. Thermal properties.

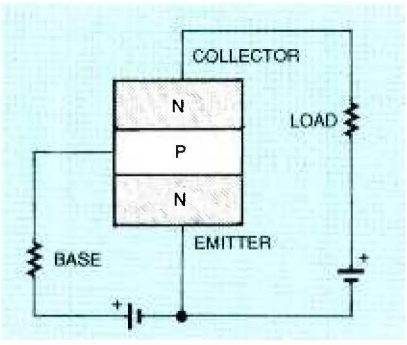

FIG. 3—FUNCTIONAL DIAGRAM of an NPN power bipolar junction transistor (BJT).

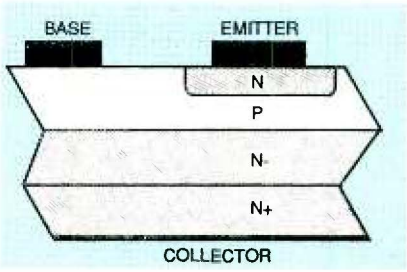

FIG. 4—SECTION VIEW of an NPN power bipolar junction transistor (BJT) with a vertical structure.

Power switching BJTs

The popularity of the switching or switchmode power supply has created a heavy demand

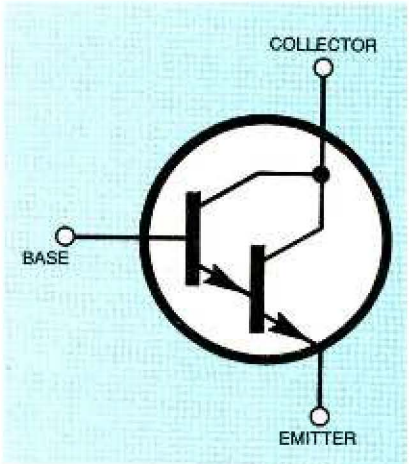

FIG. 5— SCHEMATIC SYMBOL for a power Darlington transistor.

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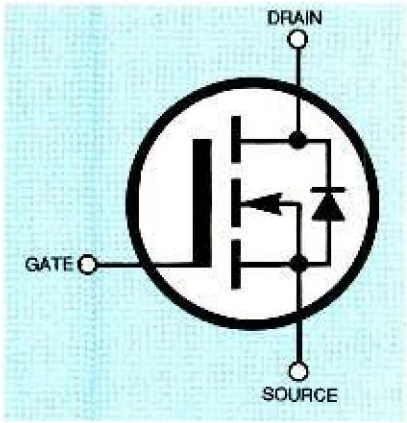

FIG. 6—SCHEMATIC SYMBOL for an N-channel power MOSFET.

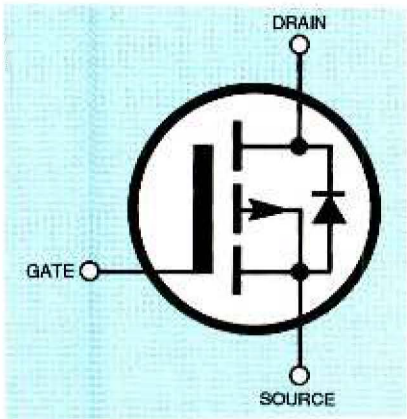

FIG. 7—SCHEMATIC SYMBOL for a P-channel, enhancement-mode power MOSFET.

for power BJTs that are capable of switching at frequencies greater than 10 kHz. To qualify for switchmode power supplies, the power BJT must be able to withstand voltage that is typically twice the input voltage.

The BJT must have a collector current rating and safe operating area (SOA) that are high enough to prevent the device from being damaged or destroyed in its intended application. The SOA quantifies the ability of the power BJT to handle high currents and voltages simultaneously.

A power BJT operated at high power densities can fail due to second breakdown. This occurs when current concentrates in a small area of the chip, causing its temperature to rise rapidly. The emitter-collector voltage could drom more than 10 volts. Input power must be shut down quickly when second breakdown to prevent the BJT from being damaged or destroyed.

Darlington power transistor

Figure 5 is the schematic symbol for a Darlington power transistor. A Darlington power transistor consists of two bipolar power transistors on a single chip that are DC coupled internally as emitter followers. Because they are packaged in discrete cases with three pins, they look like conventional power BJTs. Power Darlingtons offer higher input resistance and current gain than individual BJTs.

Power MOSFETS

Power MOSFETs are metal-oxide semiconductor field-effect transistors made to handle higher current and power than small-signal MOSFETs. Like small-signal MOSFETs, power MOSFETs are voltage-controlled devices; they have the same three electrodes: source, gate, and drain.

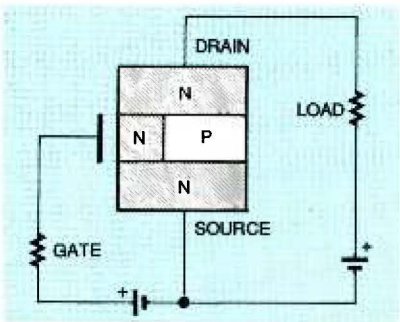

FIG. 8—FUNCTIONAL DIAGRAM of an N-channel, enhancement-mode power MOSFET

Figure 6 is the schematic symbol for an N-channel, enhancement-mode MOSFET power transistor. This schematic symbol differs from the small-signal MOSFET symbol in that it has a diode connected between its source and drain.

However, as in the small-signal MOSFET symbol, the direction of the arrow indicates the direction of conventional current flow. The broken lines representing the source to drain channel indicate that it is an enhancement-mode device. This means that it is a "normally off"device. Electrons flow from the source to the drain in an NPN MOSFET when the channel is enhanced or correctly biased.

Figure 7 is the schematic symbol for a P-channel, enhancement-mode power MOSFET. Again, as in the NPN transistors, the flow of electrons and the flow of conventional current are reversed. This can be seen from the direction of the arrowhead representing conventional current flow. (For more information on MOSFETs, both enhancement- and depletion mode, see the May 1993 *Electronics Now*, page 59.)

Figure 8 is a functional diagram for a N-channel, enhancement-mode MOSFET that is better for explaining the operation of the device. Voltage applied across the gate and source causes current to flow to the drain. The gate, as in all MOSFETs, is isolated from the source by a layer of insulating silicon oxide. With no voltage between the gate and source electrodes, the impedance between the gate and source is high and no current flows.

Figure 9 is a simplified section view of the structure of a typical power MOSFET. Unlike the planar structure of small-signal MOSFETs, most power MOSFETs today are made as vertical structures. The drain is the substrate body and its terminal is a metallized layer on the bottom. The gate and source are deposited on top of the drain structure like icing on a cake.

Most power MOSFETs today are made by the double-diffused vertical DMOS process. (It is a MOS manufacturing process involving two-stage diffusion of impurities through a single mask opening.) This geometry

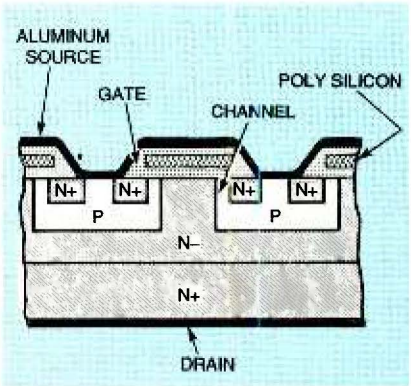

FIG. 9—CROSS-SECTION of the structure of an N-channel power MOSFET.

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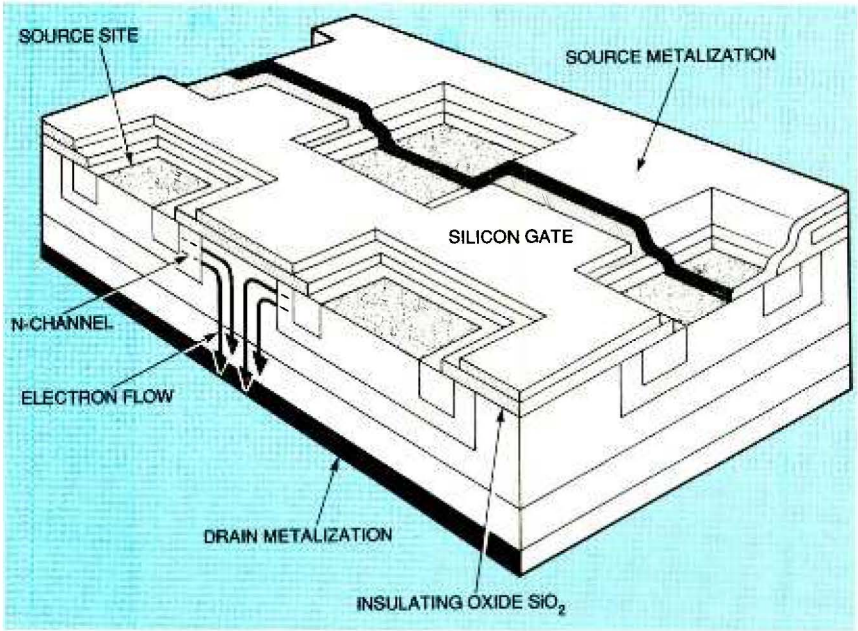

FIG. 10—CUTAWAY VIEW OF A DMOS power MOSFET. The current flows vertically from the drain to the source.

and structure has replaced the V-groove or VMOS process widely used in the 1970s.

The term vertical refers to the vertical flow of current between the drain and source as opposed to the flow of current in horizontal channels in small-signal MOSFETs and CMOS ICs.

Power MOSFET geometry.

To gain more uniform current distribution throughout the power MOSFET chip, manufacturers have developed various mesh or honeycomb gate and source structures for the upper surfaces of the chip. They define the multiple gates and sources. Figure 10 is a cutaway view of a typical power MOSFET made by the DMOS process.

The source cells consist of closed rectangular or hexagonal channels which separate a source region from the substrate drain body. The source cells are formed by an deposition process and some power MOSFETs have a density of more than a half-million cells per square inch.

Channels are formed by double diffusion at the periphery of each source cell, as shown in Figs. 9 and 10. An insulating layer of silicon dioxide is then deposited over all of the channels. A polysilicon gate pattern is deposited on top of both the insulating oxide and channel.

The silicon gate is then insulated from the source by another silicon oxide layer. All of the source cells are then connected in parallel by a continuous deposition of aluminum that forms the source terminal.

MOSFET conduction occurs when a voltage is applied between the gate and source terminals; it modulates the conductivity between the source and drain. Electrons flow from a source cell through the channel around the outside of the cell and then into the drain body.

The lower metallized surface of the drain substrate forms a conductive electrical and thermal contact with the header or mounting surface within in the device case.

International Rectifier Corp.,(IRC) developed power MOSFETs with hexagonal gate cells that HEXFETs to highlight the manufacturing process. However, Motorola Semiconductor developed rectangular gate cells, but its MOSFETs are called TMOS, a name that suggests the T-shaped flow of current in the device. This is seen in Fig. 10. Other manufacturers refer to their power MOSFETs by their own proprietary names.

Typical applications for power MOSFETs are in high-frequency switching power supplies, chopper and inverter systems for DC and AC motor speed control, high-frequency generators for induction heating, ultrasonic generators, audio amplifiers and radio- frequency transmitters.

Power MOSFETs have certain advantages over power BJTs, but these are most significant when the MOSFET is switched at high frequencies that might be 40 kHz or more. Those advantages are:

1) Faster switching speed and lower switching losses.
2) Absence of second breakdown.
3) Wider safe operating area.
4) Higher input impedance.
5) Generally higher gain.
6) Faster rise and fall times
7) Simpler drive circuitry

Power MOSFETs are priced higher than comparable power BJTs. They also have higher static drain-to-source, on-state resistance values ($R_{DS(ON)}$) that cause power losses in switching power supplies. Manufacturers have made considerable progress in reducing these values by improving their manufacturing techniques.

Power transistor packages

As in other power devices, the packaging of power transistors is influenced by the device's current ratings. The most popular case for all power transistors rated 15 amperes or less is the plastic TO-220 package. Power transistors with higher rating are packaged in metal TO-3 and TO213 metal cases among others. More recently, power transistors have been packaged in various small-outline, surface-mount cases such as the SO-8.

Thyristors defined

Thyristors are a class of gate-controlled semiconductor power rectifiers formed from four or more alternate layers of P- and N-doped silicon. The most familiar thyristors are the silicon controlled rectifier (SCR) and the bidirectional triode thyristor or triac. Less familiar are the GTO and diac.

All of these devices behave

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like conventional PN rectifiers in the presence of current passing in the reverse direction and as combination switch/rectifiers in the presence of current in the forward direction.

Controlled rectifier

The silicon controlled rectifier (SCR) is a four-layer PNPN thyristor that switches load currents in one direction only. This makes it useful for switching DC as well as half-wave and full-wave AC power. Figure 11-a shows the schematic symbol for the SCR and Fig. 11-b is a section view of its layered structure. The SCR has three junctions and three terminals; anode, cathode, and gate.

The SCR is fundamentally a rectifier diode with a control element called the gate. The anode-to-cathode voltage at which the SCR starts to conduct is determined by the current flowing in the gate electrode. The gate bias can hold the SCR off, or it can permit conduction to begin at any point in the forward half cycle of AC across the anode and cathode terminals.

The SCR anode voltage must be positive for conventional forward-biased operation. The SCR is turned on by placing a positive voltage on the gate electrode. Once it is turned on, the SCR remains on—even if its gate voltage is cut-off or made negative.

The anode-to-cathode voltage must be reduced to the threshold level or the forward current must be reversed. Also, if the SCR is switching AC, the AC must cross the zero level.

In most applications, the SCR switches currents in only one direction. SCRs can also function as controlled rectifiers in high-power bridges. Heavy-duty SCRs can handle hundreds of amperes and peak voltages as high as 1500 volts with triggering currents of a few milliamperes.

Most SCRs specified for electronics circuits are rated for 40 amperes or less. Those with higher ratings typically serve in electrical power generation, distribution, and contol applications.

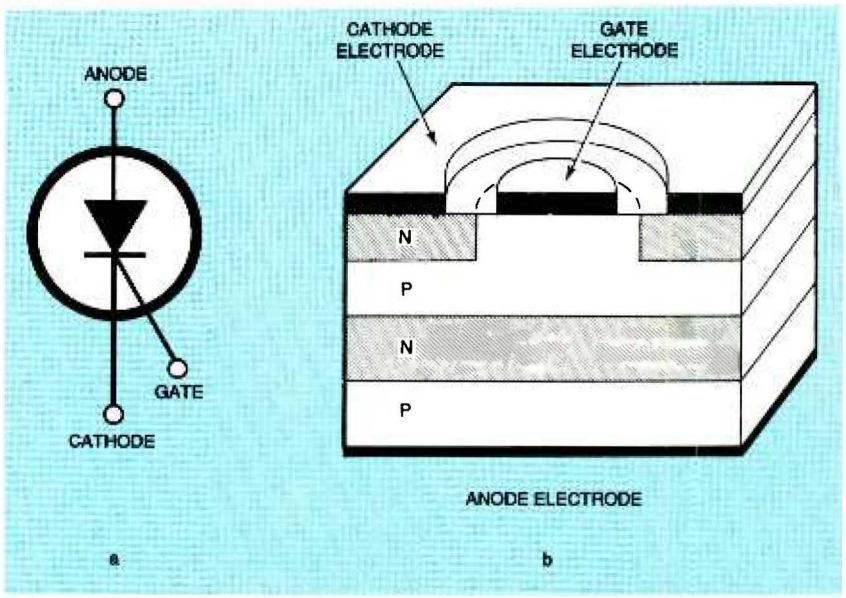

FIG. 11—SCHEMATIC SYMBOL for a silicon controlled rectifier (a), and a sectional view of an SCR chip (b).

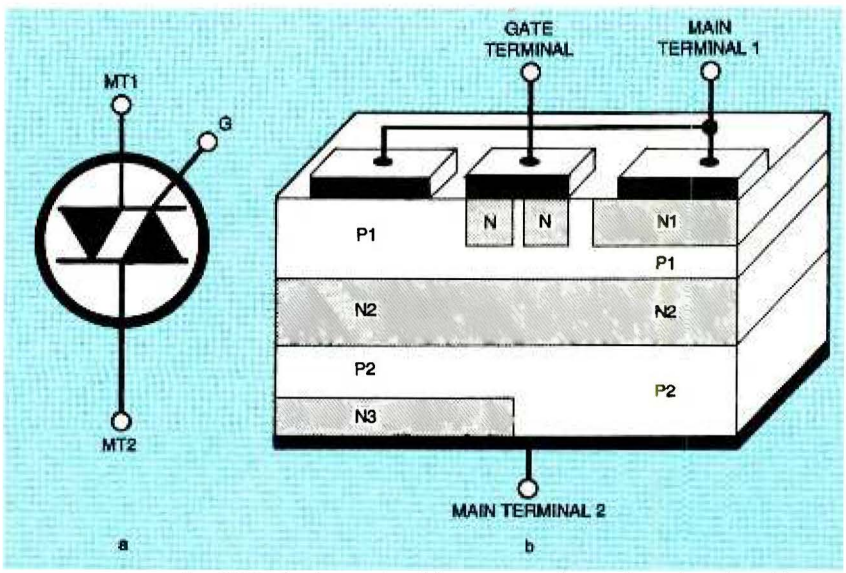

FIG. 12—SCHEMATIC SYMBOL for a triac (a), and a sectional view of a triac chip.

The gate turn-off rectifier (GTO) is a variation on the SCR. It can be turned off with a negative bias applied to its gate terminal.

Bidirectional thyristors

A triac is a bidirectional thyristor that can be turned on for load current in either direction. Figure 12-a is the schematic symbol for a triac and Fig. 12-b is a diagram of the triac's five-layer, four junction NPNPN structure. It acts like two inverse-parallel connected SCRs. A single-gate electrode turns the device on for current in both directions.

A triac is also called a gated symmetrical switch. Because triacs are bidirectional, they are widely specified for switching AC. Unlike an SCR, a triac need not be preceded by a bridge rectifier to switch full-wave AC. The electrodes of the triac are the main terminals 1 and 2, and the gate.

When a positive voltage is applied across the main terminals, a positive pulse at the gate will trigger the device into forward conduction; when a negative voltage is applied, a negative gate pulse will trigger the device into reverse conduction. Once a triac is turned

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on, the gate loses control and the device remains in its on-state until the AC voltage across its terminals falls to the triac's sustaining value or passes through the zero value.

Some triacs can switch up to 1500 volts and others can switch currents up to about 40 amperes. The restriction on current is imposed because a sngle silicon triac chip carries current in opposite directions. If the current is excessive, it will cause the chip to break down and be destroyed.

A diac is a variation of the triac without a gate terminal. Figure 13 is the schematic symbol for a diac. The device is switched on by raising the applied voltage to the breakover voltage.

Triacs are found in consumer products including power switches, lamp dimmers, appliance motor speed controls, microwave ovens, and space heaters. In addition, they are widely used as power switches in industrial and commercial solid-state relays and AC output modules.

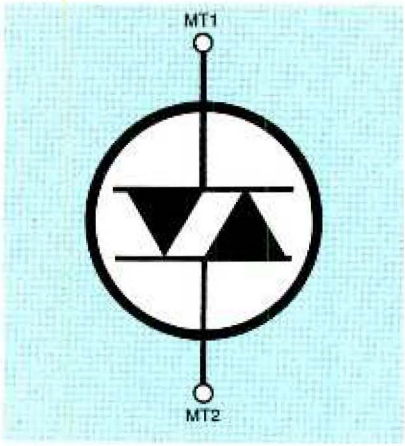

FIG. 13—SCHEMATIC SYMBOL for a diac.

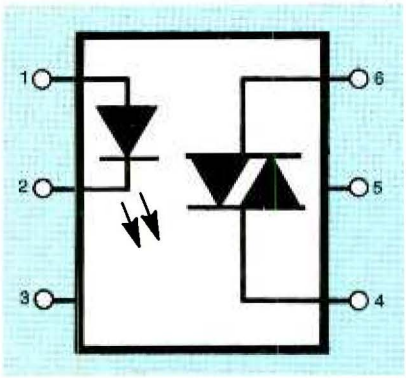

FIG. 14—SCHEMATIC FOR AN OPTOCOUPLER with a random phase photriac driver.

Thyristor packaging

Thyristors are packaged in the same kinds of cases as power transistors. Thyristors rated for more than 1 ampere are typically packaged in TO-220 plastic cases and those rated for 15 to 40 amperes are typically packaged in one of the popular metal cases.

Optocouplers

An optocoupler, also known as an optoisolator is a semiconductor device consisting of a photoemitter, a short optical transmission path and a photodetector in the same package, typically a DIP. Optocouplers are capable of converting an electrical input signal to modulated light and restoring it to an electrical signal.

The only optocouplers discussed here are those with thyristor drivers. (For more complete information on optocouplers, see the August 1992 *Electronics Now*, page 44.)

All optocouplers provide electrical isolation between the input and output circuits and are able to protect the output circuit against damaging or destructive voltage transients or surge currents in the input circuit.

The photoemitters in power optocouplers are infrared-emitting diodes (IRED) and the photodetectors can be photoSCRs or phototriacs. As in other couplers, these optothyristors are matched to the output of the IRED. The photoSCR can switch direct current and the phototriac can switch alternating current

Figure 14 is the schematic for an optocoupler with a triac driver and Fig. 15 is the schematic for an optocoupler with a zero crossing triac driver. When not receiving an electrical input, the IRED and photothyristor are normally "off." The input signal across the IRED terminals causes it to emit infrared energy that is transmitted through a short glass or plastic waveguide to the photothyristor.

Light energy incident on the photoSCR or phototriac causes it to generate an electrical output. Both photothyristors responds to input signals that might be short pulses. The internal zero-crossing circuit switches the triac only at zero crossings of the AC.

Optocoupler packaging.

All optocouplers are packaged in opaque cases to prevent the entry of extraneous light that could interfere with signal transmission. The most popular commercial/industrial optocouplers are packaged in standard six-pin dual-in-line (DIP) packages, but there is increasing demand for surface-mountable, gull-wing lead cases.

The accepted industry standard for electrical isolation (V_{ISO} is about 5000 volts AC peak, but Motorola offer optoisolators with ratings of 7500 volts. Most manufacturers seek the UL recognition as well as approval by CSA, VDE, DIN and other regulatory agencies for their products because they can switch AC line power.

Solid-state relays

A solid-state relay (SSR) is an electronic circuit that includes a signal-level trigger circuit coupled to a power semiconductor switch, either a transistor or thyristor. The term SSR is widely understood to mean a factory-made and tested product rather than a solid-state relay function built from separate components on a PC board by the user.

The SSR differs significantly in both structure and operation from the coil-and-contact electromagnetic relay (EMR). However, both provide power gain. The input circuit of an SSR might be an optocoupler, reed relay, or transformer. It is analogous to the "coil" of an EMR, and it is electrically isolated from the power semiconductor switch that acts as the "contact."" SSRs require only relatively low energy control circuits to switch the output power.

SSRs for switching alternating current require either two

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inverse-parallel (back-to-back) silicon controlled rectifiers (SCR) or an electrically equivalent triac. However, if direct current is to be switched, the switching device is either a bipolar or MOSFET transistor.

The classification of an SSR is based on its input circuit or method for achieving input-output (I/O) isolation. True SSRs achieve electrical isolation between the input and output circuits with optocouplers. Figure 16 is the block diagram of an optically-coupled, solid-state relay with zero-voltage triggering of a triac for switching an AC load. However, hybrid solid-state relays for have reed relays or transformers for isolation.

Solid-state relays have many advantages over electromechanical relays. These advantages include:

1. Longer life and higher reliability.
2. Ease in matching logic-level circuits.
3. Higher-speed switching.
4. High resistance to shock and vibration.

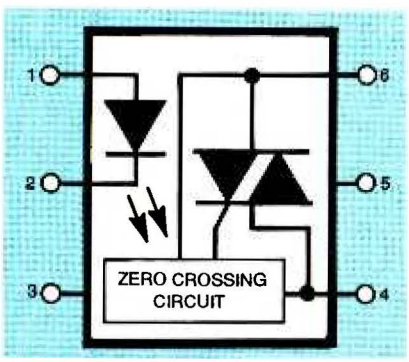

FIG. 15—SCHEMATIC FOR AN OPTOCOUPLER with a zero-crossing triac driver.

5. Absence of mechanical contacts.

The absence of mechanical contacts eliminates: contact bounce, arcing due to contact opening, electromagnetic interference (EMI), and fire or explosion hazards that would be caused by contact arcing in the presence of explosive or flammable gases, liquids or solids.

However, electromechanical relays are more cost effective in many applications that do not call for high-speed switching or operation in a hazardous environment. Many small sensitive electromechanical relays can be switched at TTL logic level.

Solid-state relays can be classified in five general groups:

1. AC power relays capable of switching 24 to 530 volts AC at 2 to 75 amperes with DC input (typically 3 to 32 volts) or AC input (typically 90 to 280 volts) with triacs or dual, back-to-back SCRs.
2. DC power relays, capable of switching 100 to 500 volts at 7 to 40 amperes under DC control with power transistors.
3. AC low-power relays, for PC-board mounting, capable of switching 60 to 240 volts at 0.3 to 4 amperes with triacs.
4. DC low-power relays, for PC-board mounting, capable of switching up to 60 volts at 3 amperes with power transistors.
5. Input-output modules, specialized miniature low-power AC and DC relays for PC-board mounting. They are widely used for interfacing computer systems and industrial controls with external sensors and actuators.

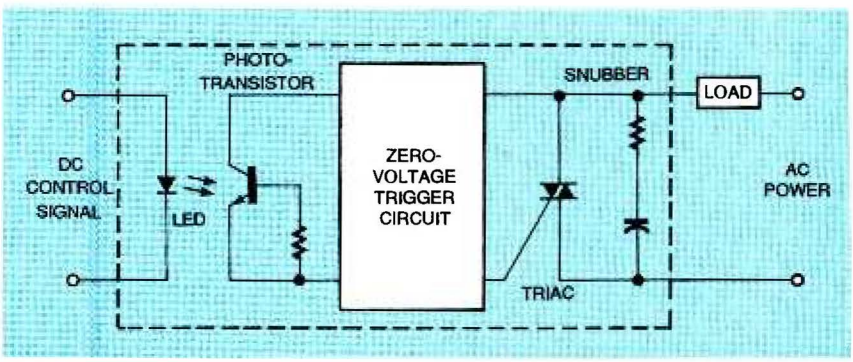

FIG. 16 —SCHEMATIC OF A SOLID-STATE AC RELAY with zero-crossing. The triac permits the relay to switch AC directly.

AC solid-state relays

The most popular AC power relays with ratings of 2 to 75 amperes are packaged in four-terminal, rectangular flatpacks suitable for panel or heatsink mounting. They have three functional sections as shown in Fig. 16: an optoisolator, a zero-voltage detector and a triac.

The zero-voltage detector assures that the thyristor will be triggered only when the AC voltage crosses the zero reference (in either the negative or positive direction) to minimize the effect of surge currents at the time the thyristor is switched.

Surge currents can result from switching tungsten-filament incandescent lamps and capacitive loads. For example, the cold resistance of a tungsten lamp is less than 10 % of its illuminated resistance.

If the SSR is turned on when the voltage is not at a zero crossing, the high instantaneous load current drawn by the lamp could destroy the SSR. The thyristor, once triggered, will not stop conducting until the load current it is conducting falls to zero.

A resistor and capacitor in series, called a snubber, bypasses voltage transients that occur with inductive loads when current and voltage are out of phase. Triacs are the thyristor of choice in general purpose AC relays for ratings up to 10 amperes at 120 to 240 volts. Dual SCRs are capable of switching AC power loads in excess of 40 kilowatts.

Important specifications for AC SSRs include:

1. Isolation voltage.
2. Operating temperature range.
3. Control signal range.
4. Must-operate voltage.
5. Must-release voltage.
6) Input current.

UL recognition and CSA approval are commonly obtained for all factory-made power SSRs for use in the United States and Canada. But there is an increasing demand for SSRs made by North American manufacturers that meet the European VDE and DIN standards so that they

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will meet European requirements as components or when installed in American-made equipment.

SS relay packaging.

The standard industry-accepted package for for AC SSRs worldwide rated 2 to 40 amperes is a rectangular flatpack that measures 2¼ × 1¾-in × 0.9-inches. Its four screw terminals permit the relay to installed (or replaced) in the field by forming hooks in the ends of the connecting wires and clamping the wires tightly with the screws.

SSR for switching direct current include optocouplers for isolation and power MOSFET drivers. The are also packaged in the flatpack cases but there is no real standardization of DC SSR package style.

Power integrated circuits

A power integrated circuit is a monolithic IC with signal-level analog circuitry or digital logic circuitry on the same chip with one or more power transistors. These ICs are capable of handling 2 amperes or 2 watts. The first commercial power ICs were drivers for high-voltage neon gas-discharge seven-segment displays. They combined bipolar digital logic with a bipolar power transistor on the same chip.

Later power ICs were made with mixed bipolar and metal-oxide semiconductor (MOS) technologies, and analog circuitry was added. CMOS logic was combined with bipolar transistors in a fabrication process called BIMOS technology. Then CMOS logic was combined with DMOS MOSFETs in a technology called CMOS/DMOS.

BIMOS technology is suitable for medium voltage and current devices. Motor controller, solenoid switcher, pulse-width modulators, and voltage regulator ICs have been made with this technology.

By contrast, CMOS/DMOS technology is suitable for applications involving either low-voltage, high-current, fast-switching or high-voltage, low-current, fast-switching ICs. Display drivers have been fabricated with CMOS/DMOS technology.

Three different techniques are used to isolate the control circuitry from the power device on the monolithic IC chip to prevent interference and electrical breakdown of the device. These are:

1. Self-isolation, an extention of CMOS technology. The reverse-biased junction is located between the source and the drain region. This technique is usually limited to devices drawing less than 2 amperes, but voltage can be as high as 500 volts.

2. Dielectric isolation (DI) employs single-crystal islands or "tubs" grown on a polysilicon substrate for locating the IC functions. Because current must be brought out of the top of the circuits within the tub, the voltage levels are limited. It is said to produce the lowest parasitic capacitance and permit full isolation on the chip.

3. Junction isolation (JI) permits the formation of both lateral and vertical ICs. An epitaxial layer is formed on the substrate and deep junctions are diffused to obtain isolated areas. Current flow is similar to that in discrete power devices.

Power IC packaging

Power ICs are being packaged in many of the same style cases as conventional ICs. However, more attention is being given to keeping junction temperatures below set limits. These include DIP cases with 8 to 28 pins and small outline (SO) cases where dissipated power is less than 2 watts.

More complex parts are being packaged in single-in-line (SIP) cases with from 11 to 23 leads. Plastic TO-220-style cases are used for power ICs that dissipate from 5 to 10 watts. Some power ICs are being packaged in plastic leaded chip carriers (PLCCs).

Power semiconductors are used in a wide variety of practical power control circuits, from simple switches to thermostatically controlled heaters. Ω

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